SMiRT-12 / K. Kussmaul (Editor)

G13/2

FRACTURE MECHANICS ANALYSIS FOR INHOMOGENEOUS MATERIAL BEHAVIOUR

L. Stumpfrock, D. Kraemer and U. Eisele

MPA Stuttgart, University of Stuttgart, Stuttgart, Germany

ABSTRACT

In the ductile fracture mechanics assessment of components the J-Integral is an important parameter. The J-Integral can even be applied to inhomogeneous materials where material laws are depending on the location., e.g., in welded joints.

Experimental and numerical investigations on CT-specimens made from a welded joint including the heat affected zone (HAZ) show the influence of the different material parameters on the J-Integral.

1 INTRODUCTION

For the fracture mechanics assessment of welded components there exist still open questions. On the one hand it is the application of the J-Integral to inhomogeneous materials. On the other hand the effects on the fracture mechanics quantities of locally varying material properties and of residual stresses resulting from welding are not totally understood. This applies to the experimental determination of fracture mechanics characteristics on laboratory specimens and for the numerical simulation of cracked components, respectively.

2 METHODS OF INVESTIGATION

2.1 Experimental investigations

Two plates of 28 mm thickness were welded together to obtain welded material on the base of 22 NiMoCr 3 7 (similar A 508 Cl.2), fig.1. Residual stresses in the weld seam were measured using the hole drilling technic and x-ray diffraction.

Various specimens were manufactured out of different areas of the weld seam, that were base material (BM), weld material (WM) and heat affected zone (HAZ). During manufacturing the specimens the residual stresses were repeatedly determined. Some specimens were annealed, to study the influence of the residual stresses.

The technological characteristics were determined on base and weld material. The properties of the HAZ resulted from specimens out of special heat treated base material (HAZ simulation).

The fracture mechanics parameters were manufactured out of the original welded joint. The crack tip was in some cases in the BM, in other cases in the WM or in the HAZ. Crack orientation was perpendicular to the weld seam as well as parallel to the weld seam in the fusion line.

The fracture mechanics experiments were conducted at 80°C. This temperature is at the beginning of the upper shelf of the charpy-V impact energy. With the help of the experimentally determined size of the stretched zone the crack resistance curves provided initiation values for J_i and $CTOD_i$.

2.2 Theoretical investigations

A valid procedure for the assessment of inhomogeneous materials as welded joints with the J-Integral parameter is actually not known. Therefore, the relations for homogeneous materials were used in the past, accepting possible deviations. In our currently running investigations the resulting deviation should be quantified and advanced computational procedures be developed.

The J-Integral is path independent for homogeneous material only; and therefore not for welded joints; so the procedure for the calculation of the J-Integral has to be modified.

A modified J is given in /1/ for piecewise constant material with sharp boundaries taking into account residual deformations. The more general case of a domain independent J-type-Integral allowing any local varying hyperelastic meterial law is given in /2/. These relations provide a J-Integral formula modified by a jump for piecewise constant material with sharp interfaces. Similar equations were given in a work more recently /3/.

The definition

$$\hat{J}_K := \lim_{\delta \to 0} \bar{J}_K(\delta) = \int_\Gamma (Wn_k - \sigma_{ij} n_j u_{i,k}) d\Gamma - \int_F ([W]n_k - \sigma_{ij} n_j [u_{i,k}]) dF$$

holds for piecewise homogeneous material. The brackets designate the jump of the respective quantities. The part of the material interface which is enclosed by the integration path Γ is called F.

For the numerical calculation of J_K by FEM data the well known method of virtual crack extension (VCE) is applied. The released energy G* caused by virtual extension Δa_k of the crack tip is

$$G^* = \hat{J}_K \Delta a_K$$

G* being defined by

$$G^* := \int_V (\sigma_{ij} \upsilon_{i,k} \Delta u_{k,j} - W \Delta u_{k,k}) dV - \int_F ([t_i u_{i,k}] - [W]n_k) \Delta u_K dF$$

This relation is transferred to a FORTRAN-procedure called MPAVIRT /4/. This procedure uses integration domains V each of which is in the 2D-case the smallest FE-covering of a corresponding annular region around the crack tip. These domains as well as the nodal virtual displacements Δu are defined as by global coordinate functions instead of being based on mesh topological information. Thus, the elements being relevant to integration are selcted automatically for any mesh topology. MPAVIRT works actually as post processor on ABAQUS results.

Calculations were carried out for plane CT-specimens with crack tips in the HAZ and the ligament in the seam or perpendicular to the seam. Elastic plastic material behaviour has been used.

The calculation of the J-Parameter is performed using the standard ABAQUS J-Integral option (VCE method) and MPAVIRT with and without the modification term.

3 RESULTS

3.1 Experimental results

The material characteristics are compiled in table 1. BM with high toughness has relatively low strength values, WM with lower toughness higher strength.The HAZ simulated materials are between BM and WM material properties.

During manufacturing the specimens the residual stresses decrease to about 20 % of the initial residual stresses, which are locally in the order of the yield stress, fig. 2.

Fracture mechanics parameters as size of the stretched zone Δa, are larger for the BM in comparison with the WM, fig. 3. HAZ values are between the extreme values. The results provided for Ji are similar. Of great influence is the position of the crack tip in the weld seam. The front of the fatigue crack runs through different structural regions, especially in the case of crack orientation perpendicular to the weld seam, so the determined values are a kind of mean value.

The influence of the annealing cannot be identified in the scatterband of the experimental results.

3.2 Numerical results

Testing of MPAVIRT has been carried out with simple linear elastic examples. In fig. 4 the path independence of the MPAVIRT J-value besides the ABAQUS J-Integral is shown. The difference in the Young's moduli chosen in order to demonstrate the influence of different material properties was considerable (factor 2).

The tested CT specimen of the experimental part were analyzed with a very fine mesh. The element size around the crack tip was 0.25 mm. Stress-strain curves determined for the different materials of the weld seam served as input for the analysis.

Each time several domains have been integrated to show the domain independence which is equivalent to path independence of the path integral formulation. The integration domains run therefore through different material regions.

For homogeneous material ABAQUS and MPAVIRT provide the same J-values, fig. 5, differencies can be seen for inhomogenous material, fig. 6.

4 SUMMARY

The experimental investigations show the reduction of residual stresses during specimen production. It was not possible to quantify the influence of residual stresses on the fracture mechanics parameters. The available numerical results show a considerable influence of the jump terms in the J-Integral formulation. An essential influence is given by the Young's modulus.

REFERENCES

/1/ Kikuchi, M., Miyamoto, H., Schindo, K.: 84-PVP-93, ASME, 1984.

/2/ Kraemer, D., W. Eckert, E. Roos und S. Krolop: Anwendbarkeit des J-Integrals bei Schweißverbindungen.13. MPA-Seminar, MPA Stuttgart, 8.-9. Okt. 1987.

/3/ Brochard, J. et al.: Energy Release Rate for Cracks in Non Homogeneous Media. Presented at IAEA/CSNI specialist's meeting "Fracture mechanics verification by large scale testing", October 26-29, 1992, Oak Ridge, Tennessee, USA.

/4/ Wagemann, G., D. Kraemer: MPAVIRT. Internal report, MPA Stuttgart, 1993.

micro structure	yield strength R_e resp. $R_{p0.2}$ [N/mm²]	ultimate strength R_m [N/mm²]	elongation A_5 [%]	reduction of area Z [%]	test temperature [° C]	young's modulus E [N/mm²]	charpy V notch impact energy A_v [J]
BM	492	629	22	72	RT		150
BM	476	640			80		150
WM	652	713	23	68	RT		≈90
WM	712	748	18	64	80	208 000	100
HAZ with annealing	741	828	17	63	80	209 500	120
HAZ without annealing	847	1135	10	49	80	206 500	70
HAZ with annealing	746	824	13	55	80	193 400	90

Table 1: Material parameters of the different structural regions

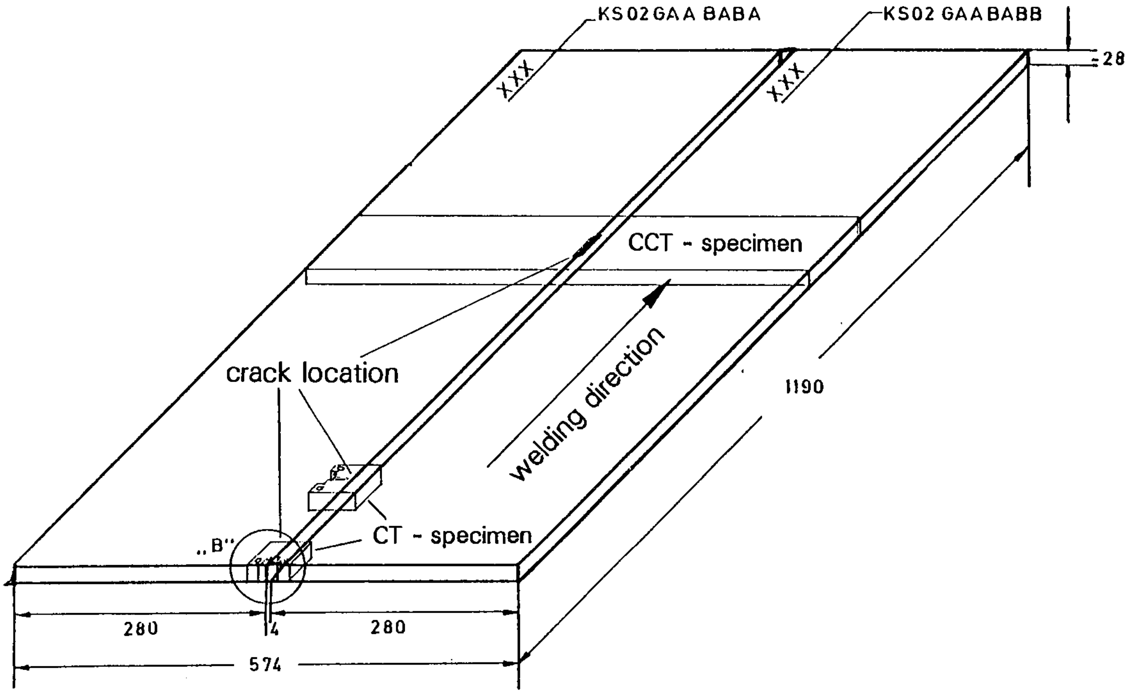

Figure 1: Welding of the seam of the plates

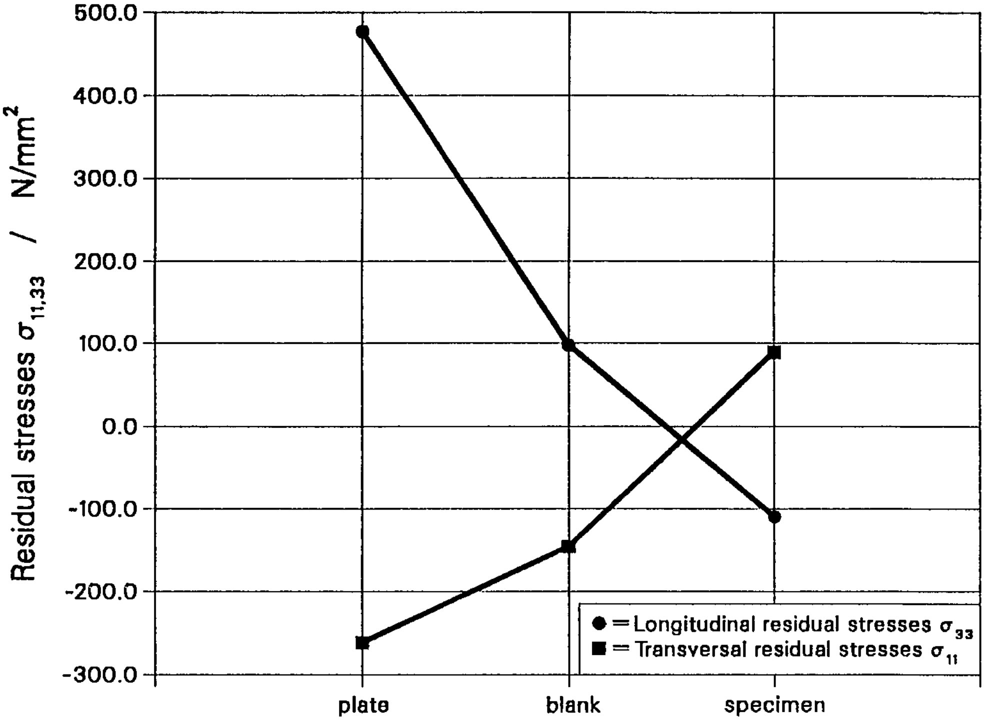

Figure 2: Residual stresses during manufacturing of a test specimen

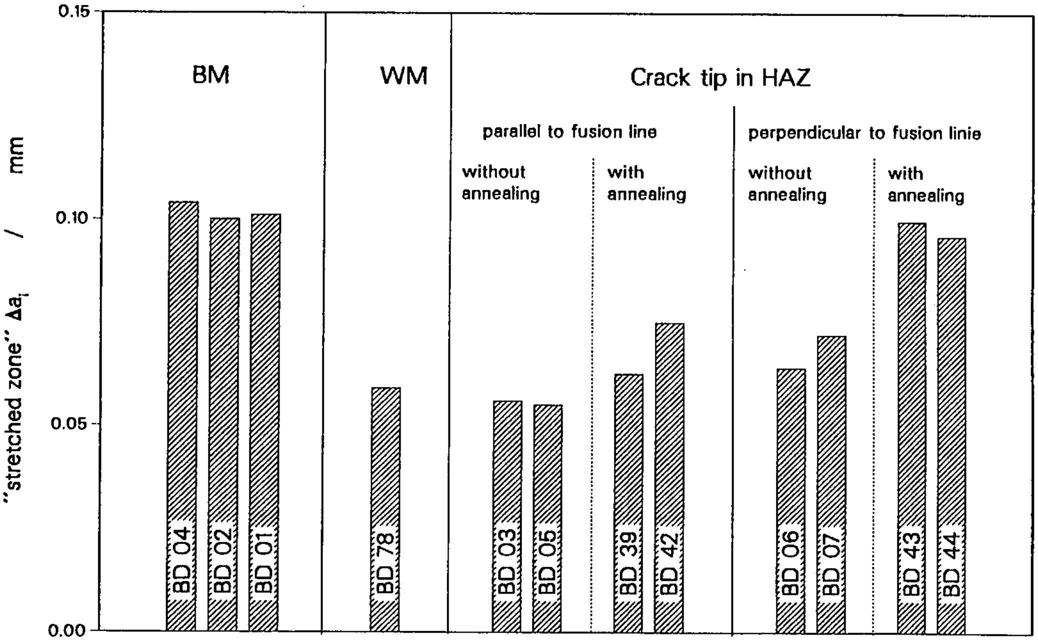

Figure 3: Stretched zone Δa_i with crack tip laying in different structural regions

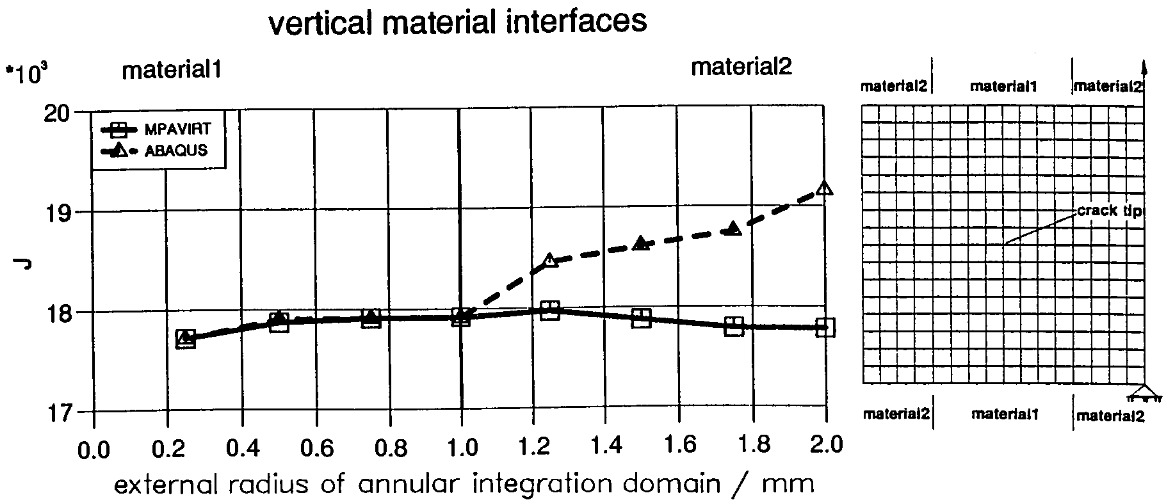

Figure 4: J-Integral for different integration domains

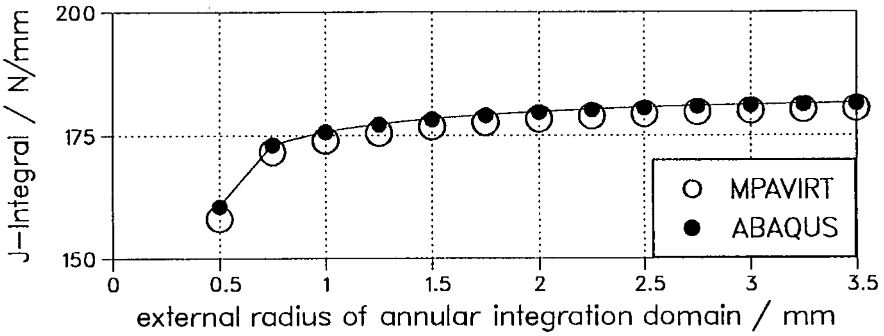

Figure 5: J-Integral for different integration domains in homogeneous base material

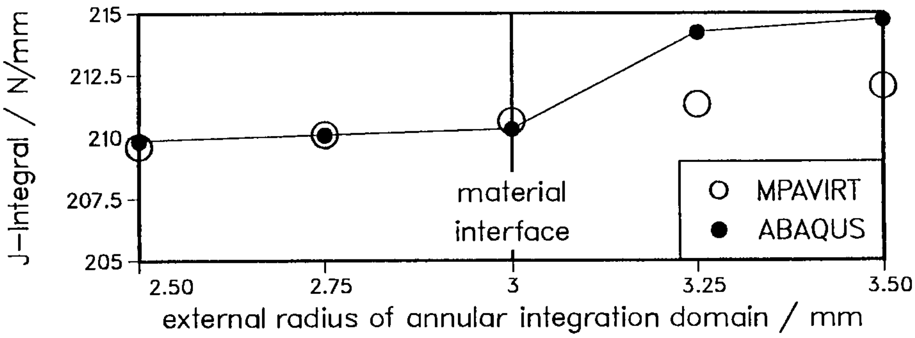

Figure 6: J-Integral for different integration domains in inhomogeneous material